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OBSERVATIONS OF BI-DIRECTIONAL LEADER DEVELOPMENT IN A TRIGGERED LIGHTNING FLASH

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1. INTRODUCTION

Recent analyses of lightning strikes to aircraft indicate that such strikes are actually initiated by the aircraft itself [1], [2] through its interaction with the ambient electrostatic field configuration. The discharge process begins with the initiation from the aircraft of a net neutral bi-directional leader system: two simultaneously propagating but oppositely charged leaders moving in nearly opposite directions. Though the aircraft studies to date on this type of discharge have provided important new information, they have also necessarily involved the formidable difficulties and complexities of such in-flight experiments. Hence, a detailed analysis of the physical processes involved has not been possible.

A more detailed study of this type of discharge could be attempted in a laboratory setting using a long air-gap arrangement. Valuable physical insights would certainly be obtained, but it is also certain that the limited length of the laboratory discharge (ten meters, for example) would preclude a full representation of the physics involved. However, this crucial experimental restriction is removed (and other advantages are realized) if artificially triggered lightning is used as the experimental format.

Rocket triggered ligthning has been used for over a decade now to allow the close observation and detailed study of large scale electric discharges. The most recent experiments have been carried out at the Kennedy Space Center, Florida [3], under the auspices of NASA with the active participation of several french and american agencies and universities.

In this paper, a unique set of observations of a modified form of rocket triggered lightning will be described. This type of triggered lightning is termed "altitude triggering" and is relevant because it has much in common with the conditions of an aircraft triggered flash. The flash of interest was triggered during the summer of 1989. This event provided an unusually good set of observations which should provide important guidance in the modeling of the bi-directional discharge.

2. DESCRIPTION OF THE EXPERIMENT

2.1. THE TRIGGERED TECHNIQUE

The classic technique of artificially triggering lightning involves the launching of a small rocket which spools out a thin, grounded, conducting wire. The wire is connected to a current measuring device on the ground. The rocket is fired when the ambient electric field observed at ground exceeds a few kV/m. The maximum height of the rocket is typically limited to 1100 m. The two key factors that determine the triggering success are the strength of the field aloft and the rocket velocity. (The rocket velocity must be greater than the ion drift velocity so as to prevent electrostatic shielding of the top of the wire).

This basic technique has been modified to trigger flashes at altitude. This is done by making the initial run of wire trailed from the rocket a non-conducting length of kevlar thread that extends to a height above ground of between 50 m and 400 m. Subsequent to this initial kevlar section, a conducting wire section is trailed out and extended in the ambient electric field aloft. With sufficient extension of the conducting wire, a discharge begins. This situation mimies that which prevails in an aircraft triggered flash.

For the particular flash described here, a short conducting length of 50 m was trailed out initially, followed by 400 m of non-conducting kevlar. The short conducting segment near ground was used to "force" the attachment to ground and thereby allow measurement of the currents of the connecting leader (see figure 3).

2.2. OPTICAL OBSERVATIONS

As depicted in figure 1, still photographs and video records of this flash were obtained from station B, located 600 m west of the trigger site. Other optical recordings were made from station C, 2.2 km south of trigger site. These observations included two streak recordings, one obtained in the near-UV and the other obtained in the visible. The near-UV recording was made with a 51 mm lens while the visible recording was made with a 24 mm lens for a wider field of view. Both recordings used a writing rate of about 22 m/s.

2.3. DIRECT CURRENT MEASUREMENTS

The devices used for the current measurements have been described in previous papers. Basically, the current is measured by recording the output voltage of a coaxial non-inductive shunt. The smaller current of the leader discharge that precedes melting of the wire was measured with a shunt of 167 milliohm resistance. Data was transmitted from the trigger site to the transient recorders and analog DC-500 kHz magnetic recorder by fiber optic links (bandwidth of DC-1 MHz for lower range and a few hundred Hz to 100 MHz for the higher range).

2.4. ELECTRIC FIELD MEASUREMENT AT GROUND

Fast electric field variations at ground were measured with two capacitive

antennas installed at 200 m and 600 m from the trigger site (points A and B in figure 1). The electric field variation between times t_1 and t_2 is a simple function of the sensor's output voltage V:

$$E(t_1) - E(t_2) = \frac{C_m}{\varepsilon_0 S}\left[V + \int_{t_2}^{t_1} \frac{1}{DT} V \, dt\right]$$

with S the effective surface of the antenna, C_m the measured capacitance, and DT the decay time constant.
The time constants of antennas A and B were 470 µs and 47 µs, respectively. Thus, for signals with a duration much longer than either of these values, the voltage, V, is proportional to the time derivative of the field. On the figures presented here, we have simply displayed the variation versus time of the voltage V; so, the electric field values indicated hold only for fast signals. However, the relative variation of the field with time is the important aspect of these observations.

3. DESCRIPTION OF THE FLASH

3.1. GENERAL DESCRIPTION

That this flash was initiated by a bi-directional leader was mainly determined by the observations of the streak camera records. The recordings clearly show a negative downward propagating leader that was initiated from the bottom of the conducting wire section aloft and which later connected with an upward moving positive leader initiated from the lowest 50 m wire section at ground. After this initial phase, the sequence of events typical of a classic triggered lightning ensued: an upward moving, positive leader propagated for about 175 ms as inferred from a negative continuous current registered at ground for this duration. (This positive leader was not recorded on the streak record). About 200 ms after the leader onset, the first return stroke occurred and was followed by 11 subsequent strokes. The overall flash duration was 0.64 s. The multiplicity of this flash was more than twice that of two earlier flashes (each had 5 strokes) triggered minutes before in the same field conditions of about 7 kV/m. The sequence of current pulses is shown in figure 2 from the records of the fast electric-field antenna A and the low frequency logarithmic current measurement. Note that the low gain channel of antenna A was sensitive to fast field variations; this record shows that there was no strong high-frequency radiation during the continuous current phase except at the end of this period when two abrupt signals were recorded corresponding to light pulses from the channel (see signals "a" and "b" in figure 2). Further details on the sequence of events in this flash from initiation of the discharge until the first return stroke are presented below.

3.2. OPTICAL OBSERVATIONS

The downward branching of the discharge channel is evidenced in the video recording from station B (see figure 3; the channel depicted was actually realized from the combination of two separate video images). The characteristics of this particular triggering technique are evident in the

recording: the straight section of channel indicates the wire section aloft prior to melting. This section of wire had reached a length of 160 m at the time of flash initiation.

The dual leader propagation presumed in a bi-directional discharge was not verified in the streak camera recording; only the downward, negative leader was imaged. Nonetheless, the existence of a positive leader, initiated from the top of the wire aloft, and starting well prior to inception of the negative leader is supported by the electric field variations recorded at ground (see figure 5a). In past experiments of this kind [5], the positive leader has invariably initiated the discharge as inferred from electric field recordings.

The onset of the downward propagation of the negative stepped leader from the bottom of the wire aloft was recorded by the near-UV streak camera and the electric field antenna B; both records are presented with a common time scale in figure 4a. Propagation of the initial leader continued for about 120 μs reaching a distance of about 20 m below the wire. At this point, the leader branched with continued simultaneous propagation of both branches toward ground. The mean step interval was 18 μs for the first 26 steps of the primary branch; the mean step interval for the branch was essentially the same, 19 μs. The typical step length was about 3 m, with a range of 1-4 m. The 2-D propagation speed for the initial leader was 2.5×10^5 m/s and 3×10^5 m/s for the branch.

Unfortunately, the field of view of the near-UV camera restricted imaging to levels above a height of 320 m. Below this level, however, both leaders were well imaged on the visible streak-camera record as shown in figure 4b. This record indicates that both leaders accelerated as they approached ground: speeds for the main and branch leader reached 3.1×10^5 m/s and 3.8×10^5 m/s, respectively. The lowest level imaged for the leaders is about 20 m above the 50 m section of conducting wire. (Recall that the purpose of this lowest section of conducting wire was to force attachment to the current measurement arrangement at ground).

The first return stroke imaged in the streak records consisted of two distinct events separated by only 5 μs (see enlarged view in figure 4c). The first of these events was a weak illumination of the main channel between the wire sections at ground and aloft. The wire was not melted at this time. The next event was a stronger illumination of the channel that involved both branches and which also initiated a fast upward propagation along the wire section aloft (speed of 1.3×10^7 m/s) for which melting is not apparent.

3.3. ELECTRIC FIELD VARIATIONS AT GROUND

The electric field variation at station B (figure 5a) indicates that an upward propagating positive leader preceded the negative leader onset by nearly a full 6 ms. Presumably, the positive leader emerged from the top of the wire section aloft. For an assumed speed of 10^5 m/s, this leader would have propagated for abour 600 m and reached a height of roughly 1200 m at the time of negative leader initiation. As the decay time for antenna B is 47 μs, the record in figure 5a is actually a record of dE/dt. The overvall field change due to the positive leader is about 1500 V/m.

In figure 5b, the electric field recordings of antennas A and B are presented on a common time scale along with the near-UV streak record of the negative leader. The step pulses measured by antenna B (600 m distant) show strong damped oscillatory structure, indicating that the field variation was primarily due to potential variations of the wire. The effect of the space

charge associated with each step is more evident in the record from the closer antenna, A (200 m distant), for which the step oscillations are much reduced. The overall duration of propagation for the negative leader was 1.13 ms as indicated in both the streak and electric field records (see figure 6a). Note that the field derivative in both antenna records was modified by inception of the branch leader: the mean dE/dt value returned to near zero but then steadily increased until connection with ground.

3.4. CURRENT MEASUREMENTS

As the negative leader approached ground, a positive leader emerged from the top of the 50 m wire section as part of the attachment process. This component of the discharge is inferred from the negative current measured by the low current channel. This current lasted for 230 µs and was pulse modulated with an interval of about 25 µs, somewhat longer than the typical negative leader step interval of 19 µs noted previously. The typical magnitude of the current pulses was about 10 A. This suggests that the pulsing of this leader was determined by the mean electrostatic conditions around the attachment wire rather than the field pulses produced by the approaching negative leader.
The current waveform for the first return stroke event also evidenced the dual pulse structure recorded in the streak images. This record is shown in figure 7 and clearly indicates an initial negative current peak of 15.8 kA with a time to peak of 2 µs and a decay to zero of only 0.78 µs. The next current pulse occurred only 4.7 µs later, reaching a peak value of 36 kA with a risetime of 0.48 µs.

The combination of current and photographic recordings indicate that the initial current pulse corresponded to melting of the wires aloft and at ground. This melting then abruptly separated the lower charged channels from the upper channel created by the leader aloft.

4. DISCUSSION

Our data reduction to date is not complete and we will continue to analyse the data to try to determine the electrostatic characteristics of the negative leader. This will entail an attempt to apply a simple electrostatic model of the leader guided by the total set of measurements as contained in the current, electric field and photographic recordings.
The consistent set of observations obtained in this case illustrate the potential for study of this important type of discharge in this experimental format. Consider the following:

1. The close observation of natural lightning negative leaders is extremely difficult for obvious reasons. A limited number of distant observations have been made, providing basic information on step lengths, step intervals and step peak currents [6]. Clearly, the conditions of observation of a triggered leader are superior to those of a natural leader. Granted, the triggered leader may not be completely developed as indicated by the shorter step lengths observed here (3 m versus 20 m). This is probably due to the limited voltage obtained by the wire in an ambient field of about 30 kV/m. On the other hand, the step interval observed here compares quite favorably with that of natural negative leaders near ground (about 20 µs).

2. The type of triggering arrangement described here reproduces much of the conditions present in a natural triggered flash initiated through the presence of an aircraft or rocket. From previous experiments, we have shown that the essential behavior is the same: the discharge is initiated by a positive leader from one end of the conductor which propagates alone for several milliseconds until the field at the opposite end of the conductor becomes large enough to launch a negative leader. The specific mechanisms of the bi-directional discharge remain to be quantitatively studied and modelled.

3. The technique of altitude triggering provides a more realistic format to study the attachment process. Accepting that a scaling factor may be involved with respect to natural flash leaders, such experiments could provide the basis for the formulation and testing of models that better describe the physics of the attachment process than can be achieved within the severe limitations of laboratory gap experiments.
   Regardless of the specific objective of such triggered experiments, it is clear that a critical piece of information required for most model studies is specification of the vertical profile of electric field, from which the discharge draws its energy. Hence, for future studies two new experimental configurations must be attempted:

   a) detailed studies of triggered discharges initiated at altitude for relatively low altitudes (500 m or less) concurrent with atmospheric field profiles up to 1000 m or so;
   b) attempts at triggering at altitude to heights of several kilometers as suggested by electric field profiles obtained to heights up to 8 km.

   These two experiments will form the basis of an experimental program we intend to conduct in the future with NASA, AFGL, and various associated US and french universities.

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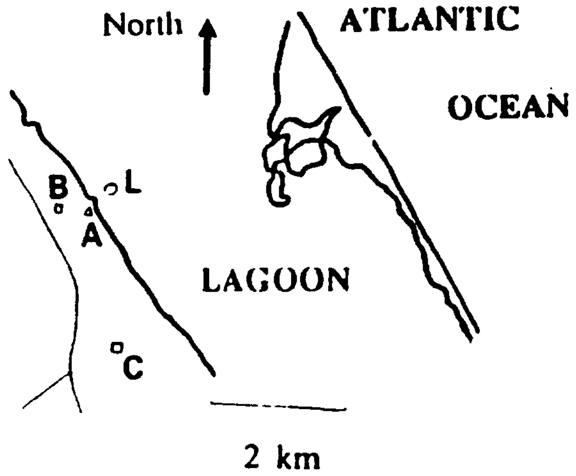


L Launching pad on water.
A Current measurements.
Fast electric field.
B Optical measurements.
Fast electric field.
C Optical measurement.

Figure 1: 1989 experiment site at KSC.

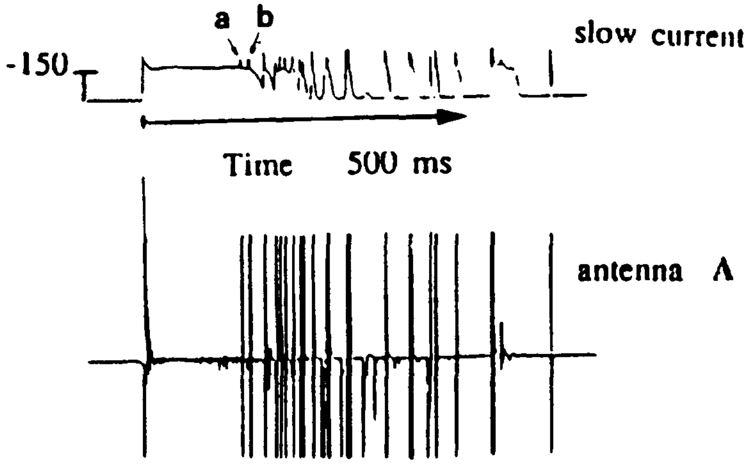


Figure 2: Timing of the flash.

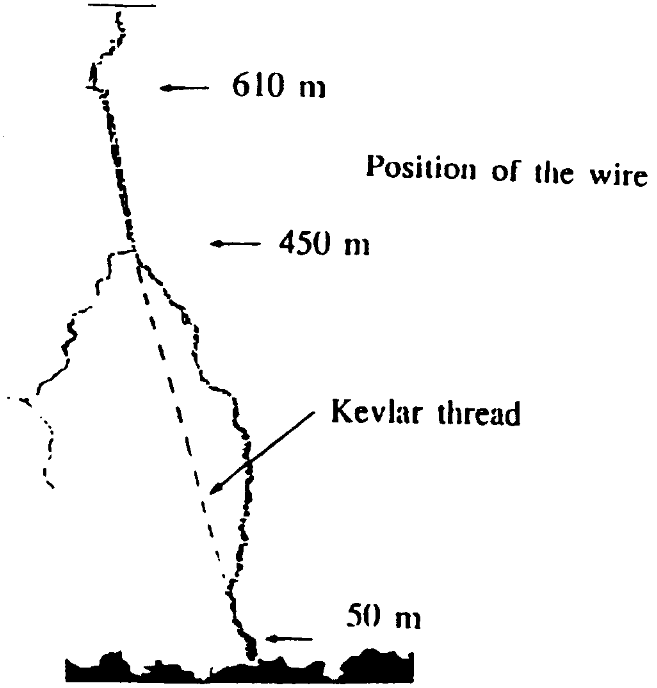


Figure 3: Component video picture from station B.

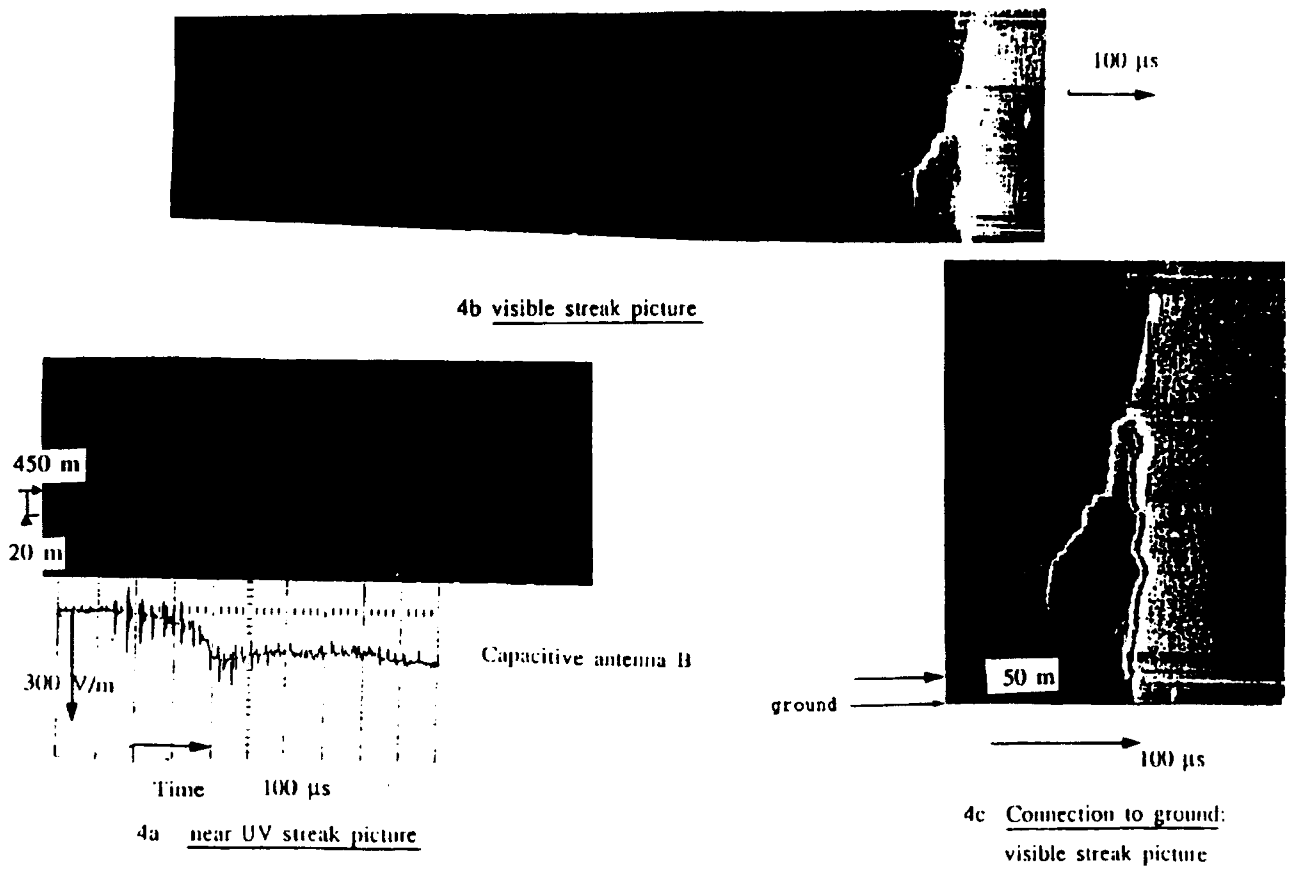
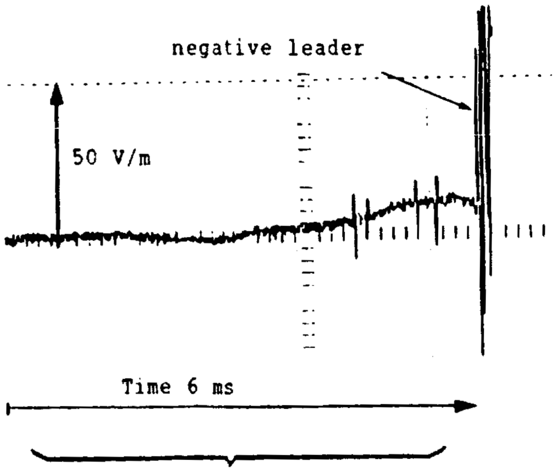
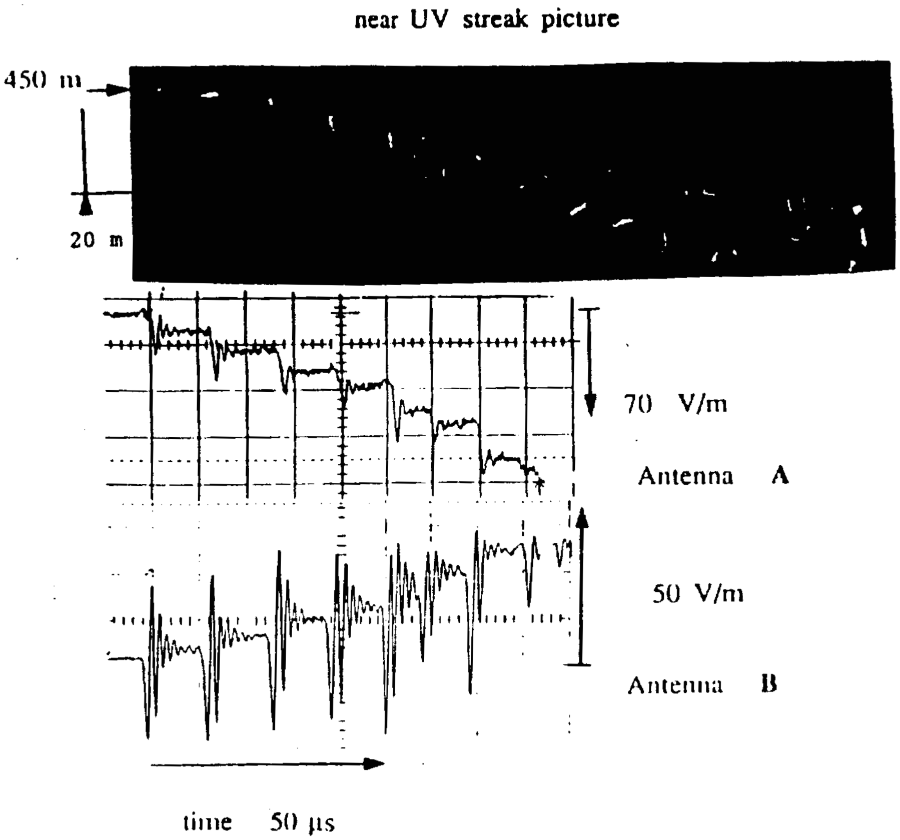


Figure 4: Streak picture of the downward negative leader.



5a positive leader onset



5b negative leader onset

Figure 5: Onset of positive and negative leader.

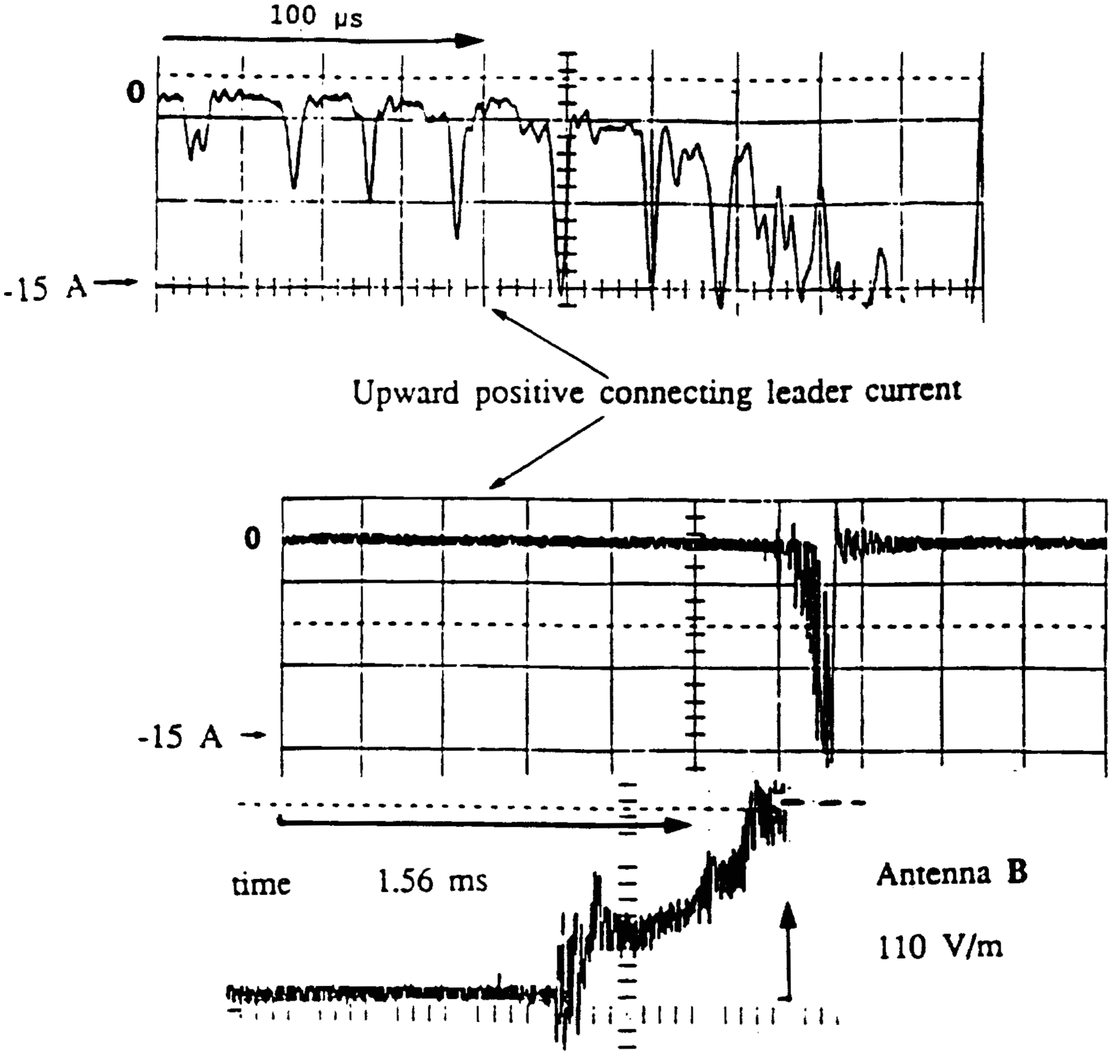


Figure 6: Connection to ground.

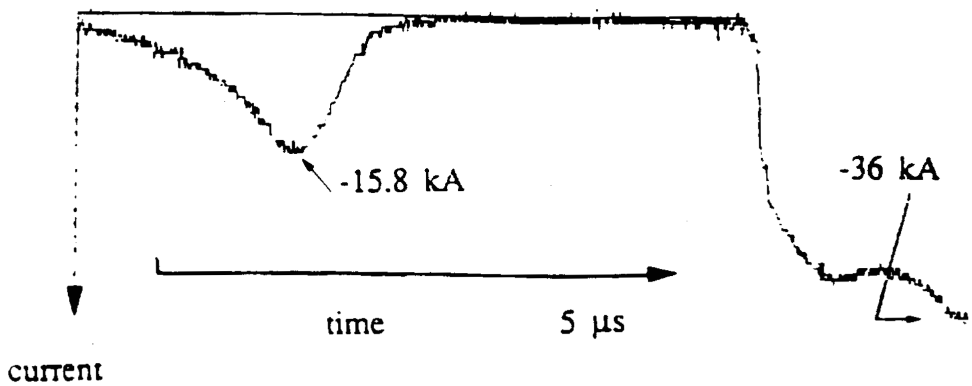


Figure 7: Current of the first return stroke.